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# Atmospheric aerosol influence on the Brazilian solar energy assessment: Experiments with different horizontal visibility bases in radiative transfer model

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ABSTRACT

The radiative transfer model BRASIL-SR is used by Brazilian Institute for Space Research for the assessment of the solar irradiation in Brazil. The model parameterizes the influence of aerosols in the solar radiation transmittance using climate averages of horizontal visibility, which does not represent the actual atmospheric condition in Brazil, especially during dry season. In clear sky conditions, aerosols are a major source of bias in solar radiation models. Their concentration have large spatial and temporal variability particularly in the Brazilian Midwestern region from April until October, due to forest fires, and in Southeastern region due to pollution from megacities. In this study, meteorological data from METAR comprising the years of 2006, 2007 and 2008 were analyzed to evaluate the seasonal variability of the horizontal visibility in Brazil to better represent the influence of aerosols on the model estimations of surface solar irradiation. New horizontal visibility values was generated to each month simulated, to provide input data to the BRASIL-SR model and site specific ground data were used to validate the model estimates. The global, direct beam and diffuse solar irradiation estimates obtained by making use of the new horizontal visibility data presented an overall lower BIAS and RMSE deviations.


## 1. Introduction

Several studies pointed out that the adoption of renewable energy, especially wind and solar, bring economic and social benefits to Brazilian society and economy ([30,31,43]). Just to mention a few, we can list the development of remote areas not assisted by Brazilian interconnected electricity distribution system, the energy security and energy planning, assistance to government programs and actions, and reduction of fossil fuel consumption and greenhouse gases emissions. However, a noteworthy barrier to solar resource exploitation, for both electricity generation and water heating, is the availability of reliable information required to a better understanding the seasonal and spatial distribution of solar resource and the climate influence on its variability [32].

From 2002 until 2006, the SWERA project (Solar and Wind Energy Resource Assessment) was financed by GEF/UNEP to provide consistent, accurate and easily accessible information on solar and wind resources for development countries like Brazil. The primary objective was to reduce the information barrier and boost up the share of solar and wind energy applications on the energy matrix (http://swera.unep.net). The Brazilian Solar Energy Atlas [35] was the main outcome concerning the Brazilian solar energy resources. The model BRASIL-SR was used to provide the solar irradiation data taking into account satellite and environmental data (temperature, relative humidity and albedo) from 1995 until 2005 [30]. The solar radiation data provided by model were compared to ground data acquired at the SONDA network operated by INPE (http://sonda.ccst.inpe.br/) in order to investigate the accuracy of solar resource assessment in Brazil. Although the model BRASIL-SR overestimated surface solar irradiation, it has provided similar performance to other numerical models used along SWERA project like SUNNY, DLR and NREL [6]. Several aspects were risen to explain the reasons for such deviations presented by model BRASIL-SR.

Earlier studies [27,35,44,47,48]; pointed out that atmospheric aerosols were the key factor associated to deviations observed in solar irradiation estimates for cloudless sky conditions during dry

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season in Central and Northern regions of Brazil. Around 80% of biomass burning occurs in the tropics, emitting large amount of gases and particles [16] and affecting the radiative balance of the atmosphere [13,24]. In Brazil, from April to October, the low relative humidity and reduced precipitation provide favorable conditions to biomass burning in rural areas, mainly in Central and Northern region, which can be caused by natural reasons or anthropic actions [40].

In addition, seasonal variability of meteorological conditions has a direct influence on the aerosol amount in the atmosphere. The residence time of atmospheric aerosol is larger during the dry season due to the lower effectiveness of removal processes [3,18]. This feature is important in the Brazilian Southeastern region, where the largest urban centers are located. The aerosol concentration has a peak on dry season in the megacities area due to fossil fuel consumption for transportation, and resuspension of soil particles due to socioeconomic activities, mainly, industrial production [4,9,10].

[1] noted a huge contrast in aerosol properties between biomass burning areas and areas not affected by fire spots events. However, even in regions with less burning biomass events, higher concentrations of trace gases and aerosols can be found due to atmospheric transport. [8] verified that pollution contaminants were transported by ocean breeze from industrial areas in the Great ABC to São Paulo city and [25] have showed that aerosols from burning biomass transported from Brazilian Northern and Midwestern regions can be found in São Paulo metropolitan area. They also notice that 20–25% of tropospheric aerosol amount was usually in the first 3 km above the surface. [36] while performing a transit flight over the coastal region in Southern Brazil observed plumes of aerosol from burning biomass regions in Northern Brazil as far south as in Porto Alegre area (distances larger than 1000 km).

The complex influence of aerosols in radiative balance has been evaluated in several studies [7,13,24,34,37,49]. It is a consensus that aerosols have an important effect on the Earth's radiation budget due to directly, by absorbing and scattering radiation, and indirectly, by altering the formation and precipitation efficiency of clouds. Radiative forcing of climate by aerosols is thought to be similar in magnitude, but of opposite sign, to that of greenhouse gases [37]. Absorption and re-radiation of longwave radiation by greenhouse gases warms the Earth-atmosphere system, whereas aerosols are thought to have a net cooling effect [2,22]. have observed attenuation up to 25 W/m$^2$ in the solar irradiation at the surface due to the increase in aerosol optical thickness caused by the biomass burning events [38,39]; also mentioned that high aerosol concentration causes a significant decrease in solar irradiation at surface with instantaneous peaks reaching up to −300 W/m$^2$ and average values of −28 W/m$^2$ from Alta Floresta during biomass burning season.

Several works [12,17,19,39] found relationships between higher concentration of atmospheric aerosols and increase of the deviations in the solar radiation estimates. The aerosol parameterization used in model BRASIL-SR is quite simple and is based on climate average of horizontal visibility data. This parameterization is not able to simulate the aerosols behavior due to biomass burning and urban and industrial emissions in Brazilian megacities [35].

This work represents the continuity of the study published by [29]; that discusses the influence of the biomass burning aerosols in the assessment of solar energy resource and describe operational parameterization for the aerosols. This earlier study showed that the systematic deviations between ground measurements and solar irradiation estimates in clear sky conditions were up to 2.5 times larger near induced forest fires in Brazil. The objective here is to improve the performance of the model BRASIL-SR by updating the surface horizontal visibility data according to observations acquired at met stations throughout the Brazilian territory in order to better parameterize the aerosol contribution to atmospheric transmittance along the dry season.

## 2. Data and methodology

### 2.1. BRASIL-SR radiative transfer model

BRASIL-SR is a physical model that provides solar irradiation estimates at the surface. It has been developed at the Centre for Earth System Science in Brazilian Institute of Space Research (CCST/INPE), in collaboration with the Solar Energy Laboratory at Federal University of Santa Catarina (UFSC). The model BRASIL-SR is based on the "Two-Stream" approach to solve the radiative transfer equation. The monthly climate averages of surface albedo, relative humidity, air temperature and horizontal visibility at the surface are the input data required to parameterize physical processes.in atmosphere. The topography was described using GTOPO30 database, made available by US Geological Survey (EROS/USGS) (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info/). This database is in a grid format with horizontal resolution of 30 arc-seconds (approximately 1 km) and topographic precision up to 100 m.

The model BRASIL-SR assumes that cloud cover is the major modulation factor of solar radiation transmittance throughout atmosphere. The cloud cover data was estimated using geostationary satellite images provided by GOES operating over South America. The effective cloud cover index, $C_{eff}$, is determined by a linear relationship between clear and cloud sky radiances observed by satellite at the visible spectral band channel (0.52–0.75 μm). This index stands for the contribution of cloud optical thickness to attenuation of solar radiation [28]:

$$C_{eff} = \frac{L_r - L_{clr}}{L_{cld} - L_{clr}} \tag{1}$$

where $L_r$ is the visible radiance observed for an satellite image pixel; $L_{clr}$ and $L_{cld}$ are the visible radiances in clear and cloudy sky conditions, respectively. The $L_{clr}$ and $L_{cld}$ values for each image pixel were obtained by statistical analysis taking into consideration all the images acquired within 30-day period [29]. discussed the relationship between $C_{eff}$ and the accuracy of the solar estimates provided by model BRASIL-SR.

The solar radiation spectrum is partitioned in 135 intervals and the atmosphere column in 30 vertical layers. The following radiative processes are parameterized: clouds, absorption by atmospheric gases ($O_3$, $CO_2$ and water vapor), Rayleigh scattering (due to atmospheric gases) and Mie scattering (due to aerosols). The vertical profile for each atmospheric constituent, as well as the air temperature and atmospheric layer thickness, are established based on the standard atmosphere type defined according to the air temperature at the surface. The model BRASIL-SR assumes a linear relationship between the global irradiation at the surface and the solar radiation flux at the top of the atmosphere, $F_0$. The solar irradiation at the surface, $F_{\downarrow}$, is linearly distributed between the two outermost atmospheric conditions: clear sky and overcast sky and it can be obtained by using equation (2):

$$F_{\downarrow} = F_0\left\{\tau_{clear}\left(1 - n_{eff}\right) + \tau_{cloud} n_{eff}\right\} \tag{2}$$

where $\tau_{clear}$ and $\tau_{cloud}$ are the atmospheric transmittance in clear and cloudy sky conditions, obtained by solving the radiative transfer equation [14]. have demonstrated that this quite simple